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1 **Underwater observations of seal-fishery interactions and the effectiveness of an**
2 **exclusion device in reducing bycatch in a mid-water trawl fishery**

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18

19 **Abstract**

20 Interactions between seals and mid-water trawl operations in the Australian Small Pelagic
21 Fishery are common and can be lethal. The nature of interactions and effectiveness of a seal
22 exclusion device (SED) in mitigating lethal interactions was assessed using underwater video.
23 Recent fishing activity and the phase of the trawl operation significantly influenced
24 interaction rates; interactions increased with the amount of recent trawl activity and were
25 highest whilst the trawl was being set. Most seals accessed the trawl via the net entrance and
26 exited via an escape opening located at the base of the SED. The size of the escape opening
27 was the only operational factor that influenced mortality rates – simply enlarging the escape
28 hole reduced lethal interactions by 79%. However, since all deceased seals dropped out of
29 the net before they were brought on board they would have gone unobserved without video
30 monitoring. Limiting the concentration of fishing activity in space and time and refinement
31 of the SED design, in particular to address dropouts, is recommended if mortality rates are to
32 be reduced.

33
34 **Key words:** Marine mammals; pinniped bycatch; mid-water trawl; seal exclusion device;
35 underwater video; south-eastern Australia

36

37

38 Introduction

39 Direct interactions between fishing gear and marine mammals occur in many fisheries
40 worldwide, posing a significant threat to the viability of some populations (Chilvers 2008;
41 Read 2008; Underwood et al. 2008). Globally, the bycatch of pinnipeds and cetaceans is
42 estimated to be in the hundreds of thousands of individuals, although these estimates are
43 almost certainly conservative due to a lack of information for many fisheries (Read et al.
44 2006; Read 2008; Moore et al. 2009). Gillnet fisheries account for the bulk of the marine
45 mammal bycatch (Read et al. 2006; Reeves et al. 2013), with varying levels of bycatch
46 occurring in trawl fisheries (Northridge 1991; Fertl and Leatherwood 1997; Morizur et al.
47 1999; Shaughnessy et al. 2003).

48 A variety of non-gear specific management strategies have been implemented to
49 reduce marine mammal bycatch in trawls. These include trigger limits for bycatch, effort
50 restrictions and temporal and/or spatial closures (Wilkinson et al. 2003; Smith and Baird
51 2005; Chilvers 2008). In addition, codes of practice have been developed to reduce
52 interactions. These codes typically include measures such as ceasing fishing operations when
53 marine mammals are sighted, moving vessels away from areas where marine mammals are
54 present, and spatial and temporal restrictions on fishing to avoid periods of highest risk
55 (Wilkinson et al. 2003; Tilzey et al. 2006; Chilvers 2008; MPI 2013). A variety of exclusion
56 devices including selection grids (Hamer and Goldsworthy 2006; Zeeberg et al. 2006;
57 Wakefield et al. 2014), barrier nets (van Marlen 2007) and acoustic mitigation devices
58 (pingers) (van Marlen 2007; Northridge et al. 2011) have been used in trawl nets to reduce
59 marine mammal bycatch. Generally modifications to gear and/or fishing practices have
60 failed to produce definitive results as to their effectiveness, this is largely because the
61 interactions and their outcomes are difficult to observe (Wilkinson et al. 2003; Northridge et
62 al. 2005, 2011; Hamer and Goldsworthy 2006; Hamilton and Baker 2015). Warden and

63 Murray (2011) note that a critical factor in both the development and evaluation of mitigation
64 measures is understanding the nature of the interactions and the consequences for the animals
65 involved.

66 The Australian Small Pelagic Fishery (SPF) is at an early stage of development.
67 Principal target species include redbait (*Emmelichthys nitidus*) and jack mackerel (*Trachurus*
68 *declivis*) which are taken mainly from the continental shelf waters around Tasmania
69 (Woodhams et al. 2011). Mid-water trawl operations commenced in 2001 with landings
70 peaking at over 11 000 tonnes in 2003-04. Fishing effort declined from 2007 and ceased in
71 2009, due mainly to economic limitations of the sole active trawl vessel which was unable to
72 process catches at sea. An attempt to introduce a large factory freezer trawler into the SPF in
73 2012 proved highly controversial. A sustained campaign from conservation and recreational
74 fishing groups resulted in the Australian government imposing a two year moratorium on
75 vessels larger than 130 m, subject to a review of the environmental impacts of such an
76 operation (Tracey et al. 2013). One of the key issues noted for review was the potential for
77 marine mammal bycatch. A permanent ban on fishing vessels over 130 m was implemented
78 in 2014 following the release of the expert panel report (Anon 2014). In early 2015 the main
79 operator in the SPF introduced a smaller (95 m) factory trawler, again triggering protests
80 from groups concerned about the potential ecological impacts of large-scale trawl operations,
81 including the bycatch of marine mammals. These concerns proved well founded with
82 multiple reports of dolphin and seal bycatch occurring shortly after operations commenced,
83 highlighting the urgency to refine bycatch mitigation measures.

84 From the outset of mid-water trawl operations in the SPF the sole operating vessel
85 deployed a rope mesh grid, with an escape hole located at the top of the net, to prevent large
86 megafauna from entering the codend. No marine mammal bycatch was reported until
87 October 2004, at which time 14 dolphin mortalities occurred in two separate hauls. A high

level (100%) of observer coverage was implemented along with a code of practice specifying that if dolphins were sighted around the vessel the trawl would not be deployed and it would move at least ten kilometres from the area prior to setting the gear. Over the following seven months there were three additional incidents involving eleven dolphin mortalities and three separate incidents involving three seal mortalities. An underwater camera was installed on the trawl net between June and September 2005 in an attempt to better understand the behaviour of marine mammals in relation to the fishing gear. Fur seals (*Arctocephalus* sp.) were observed entering the net in over half of the 19 trawl shots that were monitored (Browne et al. 2005). Several aspects of the excluder design were identified for improvement, the most notable being that the mesh barrier deformed considerably under the weight of a seal, sometimes leading to partial entanglements. The vertical orientation of the barrier also provided no obvious passive assistance in directing the seals out through the escape opening. Furthermore, large quantities of target species were observed exiting via the escape opening while the majority of the seals (11 out of 13) observed within the net had entered via the escape opening (Browne et al. 2005). As a consequence the vessel's operators replaced the mesh barrier with an inclined steel grid or seal exclusion device (SED) with the escape opening located at the bottom of the net.

The present study builds on the pilot study by examining the frequency and nature of the interactions between seals and mid-water trawl gear under commercial fishing conditions. This research has particular relevance to the on-going refinement of strategies to reduce bycatch mortality in the SPF and is especially important as industry seeks to further develop this fishery and address public concern over marine mammal interactions.

Materials and methods

General

Mid-water trawl operations undertaken by a 50 m commercial fishing vessel, the sole trawler operating in the SPF, were monitored between March 2006 and January 2007.

Fishing activity was concentrated in three discrete regions, off the north-east, south-east and south-west coasts of Tasmania (Figure 1). The mid-water trawl used between March and August 2006 had a wing spread of approximately 48 m and head line height of between 30 – 35 m whilst fishing. The operator replaced this with a larger net in September 2006, the replacement had a wing spread of about 60 m and 40 - 47 m headline height when fishing. In both nets the distance between the headrope and extension piece where the SED was located was around 150 m, with the codend extending a further 55 m.

A purpose built camera system capable of recording the entire trawl operation and being operated by the vessel's crew was designed for this study. Responsibility for decisions relating to the deployment of the camera system remained with the vessel master and fishing company but with the objective of achieving a high level of operational coverage.

SED configuration

The SED was comprised of two panels, each with ten vertical steel bars spaced at 21 cm, to produce a 2.3 x 2.3 m steel grid. The SED was angled forwards at about 15-25°, with an escape opening located at its base. Two configurations were trialled during the study period. A 1 x 1 m escape opening ('small escape opening', Figure 2a) was used initially. In mid June 2006 this was enlarged to 1.9 m wide ('large escape opening', Figure 2b) and used for the remainder of the study period. The escape hole was either left unobstructed (open) or had a loose skirt of netting (small escape opening) or short lengths of rope attached to the leading edge (large escape opening). The netting and trailing ropes were introduced in an attempt by industry to discourage the loss of target species out of the hole whilst not hindering the exit of large animals. Of the trawls successfully monitored using the underwater

camera, 16 out of 30 involving the small escape opening and 6 of 48 involving the large escape opening had no obstruction to the escape opening.

Camera system

A black and white 0.05 lx analogue camera with a 90 degree diagonal wide angle lens (Scielex Pty Ltd, Tasmania) was coupled to a hard drive unit (Archos AV 500 mobile digital video recorder). Lighting was provided by a single Luxeon 3 watt LED light with a diffuser to reduce the 'hotspot' lighting effect. Power was supplied by a 14.8 V 10 Ah lithium ion battery which provided a run time of over 15 hours for the light, camera and recorder. The camera unit was protected by an external housing that was designed to slot into a metal frame sewn into the top of the trawl net and was positioned about 3 m in front of the SED. The camera was orientated to face the codend, providing a view of the SED and escape opening.

The time signal associated with the video footage was matched to the time that the camera entered the water at the start of each trawl shot and any details noted while reviewing the footage were assigned a time of day and elapsed trawl time. Date, times (trawl start and finish, camera in the water), shot location (latitude and longitude) and bottom depth were recorded for all trawl shots when the camera was deployed. These data were matched against compulsory logbook records to provide additional operational and catch information.

Trawl operations

Trawls were split into five operational phases - setting, fishing, turning, hauling, and pump-out - based on a combination of observed changes in net geometry, water flow, fish behaviour and elapsed trawl time. It usually took 20-30 min for the net to reach fishing depth, with the net spreading and filling out during the process and causing the SED to straighten (*setting* phase). Whilst in the *fishing* phase, the net appeared tight and stable on the video, with tow speeds ranging between 5.5-9 km h⁻¹ (mean 7.2 km h⁻¹). Trawls occasionally

involved manoeuvres ranging from small changes in course to U-turns. Small changes in direction or long gradual turns were not usually detectable by video. Sharp turns were readily distinguishable as they involved winching the trawl boards to the surface, turning sharply to run back over fish marks before then resetting the gear (*turning* phase). The *hauling* phase was associated with a marked drop in tow speed (flow rate) which was observed as a softening and increased instability in the net structure. After the net reached the surface the codend was typically drawn alongside the vessel and the catch pumped directly into the fish holds. During this *pump-out* phase the remainder of the net, including the extension piece containing the SED, was streamed behind the vessel as it moved ahead slowly. Depending on the size of the catch this phase took 0.5-2.5 h to complete.

Analysis of video data

Video records were divided into 30 min time blocks, commencing from the time the camera entered the water. Each video block was assigned one of the previously defined operational phases. In practice, some video blocks encompassed more than one trawl phase and in such cases if more than 20% of the video block involved either setting, turning or hauling, the entire block was assigned to one of these phases. This protocol recognises that changes in net geometry are likely to pose a greater risk to marine mammals inside the net. By default the net was assumed to be in the fishing phase if it appeared tight and stable and there was no evidence of variability in water flow or other indicators of alternative trawl phases.

A variety of descriptive and behavioural information was recorded for each interaction event involving marine mammals. Information included interaction start-time, species involved, relative size (large, medium or small), condition (active/alert, weak/disorientated or unresponsive), mode of entry into the field of view (from behind the camera or via the escape opening), duration of the interaction (time observed in view), and

mode of exit from the field of view (back up the net or expelled out of the escape opening). For each interaction event a judgement was made as to whether the sighting represented a new individual or a repeat sighting. Factors such as the time interval between sightings, size and condition of the animal, and outcome of the most recent sighting were taken into account. An individual that was sighted within five minutes of a previous sighting and was of similar size was flagged as potentially the same animal returning. Exceptions to this rule occurred where i) the individual in the previous sighting event had been expelled through the escape opening, ii) individuals were physically identifiable as being different (markings, colour or size), and/or iii) if the behaviour of the latter individual suggested otherwise. For instance, seals that were active and alert even after an apparent five minute gap between sightings (or a combined interaction time to that point that exceeded 7-8 min) were assumed to have been different individuals. This was based on the assumption that individuals are expected to become increasingly stressed as dive times approach normal breath-hold limits (Hindell and Pemberton 1997; Arnould and Hindell 2001). In this way it was possible to infer when an animal first entered the camera field of view, the trawl phase at that time, its mode of access to the net, duration within the net and final outcome of the interaction. Individuals last sighted swimming towards the net mouth were assumed to have escaped somewhere in the trawl forward of the SED, such as net mouth or through the large meshes in the fore portion of the net. In practice, factors such as sub-optimal camera orientation or obscuring effects when large quantities of target species passed down the net meant it was not always possible to clearly observe the final outcome for each interaction event. In such situations the outcome was recorded as uncertain. Overall, 139 out of 203 (68%) re-sighting events occurred within one minute and 190 (93.5%) within three minutes of the previous sighting. Video records involving interactions were reviewed independently by a second observer and

any inconsistencies in interpretation were subjected to further scrutiny before an agreed interpretation was accepted.

For comparative purposes and to reduce potential errors arising from the identification of individual animals, interaction events were also analysed as if they were independent occurrences. Whilst this approach removed subjectivity, it limited the ability to make inferences about the nature of the interactions and gives higher weight to individuals which moved in and out of the field of view multiple times.

Data analysis

Interaction rates

Generalised linear models (GLMs) were used to investigate factors influencing the rate at which seal interactions occurred. The dependent variable was the number of identified seals (based on initial sighting) in each 30 min video block. Covariates considered were season, time of day, trawl phase (setting, fishing, turning, hauling, pump-out) and the level of recent fishing activity. For season, the year was divided into quarters (Q1=Jan-Mar, Q2=Apr-Jun, etc.) while time of day (based on video block start time) was divided into four hourly time periods (00:01-04:00, 04:01- 08:00, etc.) to ensure sufficient data was contained in each of the time period categories. Recent fishing activity was included to assess the potential for behavioural habituation to the fishing activity of the vessel. The recent fishing activity was defined as the number of trawl hours by the vessel in the specific region (i.e. north-east, south-east or south-west coasts) in the previous ten days. A ten day window was selected after comparing the Akaike Information Criterion (AIC) for models with windows of different durations.

A poisson error distribution (with a log link) represents an appropriate first model choice as the independent variable consists of counts. However, video evidence suggested that seals occasionally arrived in groups, with the time between groups and the size of the

groups likely to be driven by separate processes. This would present as over-dispersed data. To explore this possibility a negative binomial distribution and a zero inflated negative binomial regression were also considered. The negative binomial distribution provided a substantially better fit as suggested by a likelihood ratio test ($p < 0.001$). The zero-inflated negative binomial regression did not provide an improved fit to the data ($p = 1$), hence the standard negative binomial regression was used. Model fitting began with the fully saturated model and variables were then removed, one at a time, on the basis of a likelihood ratio test with the reduced model.

To test the sensitivity of the interaction rate model to the assumptions in the seal identification process, the same modelling was conducted using unadjusted seal sightings (i.e. interaction events) in each 30 minute period as the dependent variable.

Interaction duration and outcomes

Interaction durations (time between first and last sighting) for identified seals were compared based on outcome, i.e. whether individuals escaped by swimming out of the net entrance (Escaped) or exited via the SED opening (Expelled) whilst still responsive (i.e. excluding mortalities). Since the mode of exit for some seals was not directly observed an additional category (Uncertain) was recognised.

Seals judged as mortalities generally lay motionless against the SED or the netting near the escape hole for long periods, in some cases up to several hours. For a subset of the mortalities it was possible to estimate how long individuals continued to exhibit overt responsiveness, a measure that has relevance when considering the relationship between interaction duration and survival potential.

Interaction durations and duration of overt responsiveness for mortalities were compared using one-way ANOVA and post-hoc pairwise t-tests with Bonferroni adjusted p-values.

259 *Mortalities*

260 Operational factors influencing lethal interactions were explored using logistic
261 regression where the interaction outcome for each seal was binary (mortality or potentially
262 survived). Factors considered in the mortality model included SED configuration (small or
263 large escape opening), escape opening (open or partially obstructed), time of day, trawl phase
264 and recent fishing activity. Whether the escape opening was left open or partially obstructed
265 with a mesh skirting or ropes was tested as a factor to examine if this may have influenced
266 the interaction outcome. Non-significant parameters were removed sequentially on the basis
267 of least influence on the AIC.

268 An estimate of the total number of seal mortalities attributable to the mid-water trawl
269 operation during the study period was also undertaken by imputing data for the unmonitored
270 shots using bootstrapping, with 95% confidence intervals determined using the percentile
271 method. The bootstrap was based on 1000 iterations and was stratified by SED configuration
272 since this was the primary factor influencing the mortality rate.

273 **Results**

274 **General**

275 During the study period 190 mid-water trawl shots were undertaken by the fishing
276 vessel targeting shelf waters off Tasmania. Trawls were generally fished close to the bottom
277 in depths averaging 119 m (range 65 – 240 m) and trawl duration (excluding pump-out)
278 averaged 6.2 h (range 0.65 – 13.75 h). Redbait accounted for almost 90% and jack mackerel
279 a further 8% of the total product weight landed by the vessel.

280 The underwater camera system was deployed on 114 occasions and produced useable
281 images for 78 trawls (41% of all trawl shots) (Table 1), representing about 650 hours of video
282 footage. Video coverage of the entire fishing operation was achieved for 51 shots; partial

coverage of the remainder resulted from failure to download all files, corrupted files, or equipment failure part way through trawl operations.

Interactions with megafauna were observed in 55 (70%) of the monitored trawls, with fur seals observed in 52 (67%) trawls, 49 (63%) of which involved seals wholly within the trawl net. In eight trawl shots fur seals partially entered the trawl net via the escape opening before retreating, these seals were excluded from subsequent analyses. While species could not be readily distinguished, the spatial distribution of the interactions suggest that most if not all were Australian fur seals (*A. pusillus doriferus*) rather than the closely related New Zealand fur seal (*A. forsteri*) (M.A. Hindell, pers. comm.). Other megafauna observed on video included thresher sharks (*Alopias vulpinus* – seven trawls involving ten individuals), sunfish (*Mola mola* – three trawls involving four individuals) and a single unidentified species of ray. No dolphins were observed on video nor reported as bycatch during the study period.

Seal interactions

An estimated 146 seals, represented by 352 interaction events, were observed inside the trawl (Table 1). Up to eleven seals were recorded in a single trawl but in the majority of instances (36 or 73% of trawls) three or fewer seals were observed.

The vast majority of interaction events (342 or 97%) involved seals that entered the field of view from behind the camera. Similarly, the majority (136 or 93%) of the identified seals were first observed to enter the field of view from behind the camera implying that they had entered the net forward of the SED, either via the net mouth or through the large meshes in the fore part of the net (Table 1). Seals approached the SED either swimming actively or gliding with the current created by the forward motion of the trawl. Some made contact with the SED, often more than once in an interaction event, either resting against the grid before making further responses or making immediate attempts to swim away. Others moved freely

about in front of the SED, sometimes feeding on fish. In several instances, contact with the SED resulted in individuals rolling towards the escape opening and being expelled passively or actively swimming out through the escape opening.

A total of nine seals (seven trawl shots) were also observed to swim into the net through the escape opening (Table 1), four of these individuals subsequently exited via the escape hole, one died in the net and the remaining two escaped via the net entrance or fore part of the net. The partial obstruction of the escape hole with netting or ropes did not appear to influence net entry via the escape hole as only two seals accessed the net (same shot) when the escape hole was unobstructed. The mode of entry for one seal was not observed; this individual was first detected lying motionless against the SED after a large quantity of target species had obscured the field of view.

Interaction rates

Recent fishing activity and trawl phase were significant factors for the identified seal model while recent fishing activity and season were significant for the interaction event model (Table 2). In both models each additional hour of fishing in the preceding ten days resulted in a 2-4% increase in interaction rates (Table 3). The interaction rate whilst setting was 2.9 times higher than during normal fishing and substantially higher than whilst turning or hauling (Table 3). Whilst the interaction rate was higher during pump-out, only four individuals were involved (three entering via the SED opening) and thus the effect was less certain as indicated by a broad 95% confidence interval. Interaction events (rather than seal numbers) peaked during the second quarter (April-June) and were about half the first quarter level during the third and fourth quarters (July-December) (Table 3).

Interaction outcomes and duration

Overall, 69 seals (47% of the total number sighted) exited via the SED opening, 38 (26%) were judged to have escaped forward of the SED, and 20 (14%) were determined to have died in the trawl net. The modes of exit for the remaining 19 (13%) were not observed on video and thus were uncertain (Table 1). With the exception of the individual that was first observed motionless against the SED (noted above), each of the seals that subsequently died in the net were active or at least overtly responsive when first observed on video, suggesting that none had drowned further up the net.

Interaction times ranged from a few seconds to several hours in the case of the mortalities. Excluding the mortalities, 63% of the interactions lasted less than 3 min, with about 79% of the seals being expelled or leaving the field of view within 5 min of first sighting. The maximum interaction duration for individuals that actively escaped by swimming out via the net entrance was 6.1 min, this compared with 14.4 min for an individual that was expelled out of the escape opening whilst still exhibiting some level of responsiveness (Figure 3). By comparison, overt responsiveness in a subset of the mortalities (n=12) ceased between 4.5 and 12.7 min after first sighting.

Although there was a significant difference in interaction durations between outcome categories ($p=3\times 10^{-12}$), pairwise t-tests revealed no differences between Escaped, Expelled and Uncertain categories ($p>0.4$). The Mortality (responsiveness) category did, however, differ from each of the other categories ($p<1\times 10^{-6}$ for each comparison).

Mortalities

SED configuration was the only factor that significantly affected the outcome in the mortality model (Table 2). The model indicated that the mortality rate for the large escape opening was significantly lower, about a fifth (21%) of that for the small escape opening configuration (Table 3).

By imputing data for the unmonitored trawls the total number of seal mortalities due to mid-water trawl operations during the study period was estimated at 49 (95%CI 29 – 69), implying an overall mortality rate of 0.26 seals trawl⁻¹. It should be noted that no seals (alive or dead) were brought on deck whilst the camera was in use. Each of the mortalities eventually fell out through the escape opening before the net was hauled on board. In several instances this occurred as the net reached the surface and wave action acted to dislodge the animals from where they lay resting against the SED or netting surrounding the escape hole.

Discussion

The present study successfully applied underwater video technology to describe the behaviour of fur seals in the trawl gear, evaluate the outcomes of individual interactions and assess the effectiveness of a simple modification of the exclusion device in mitigating mortalities. There are relatively few other studies that have directly examined the nature of the interactions and, where information is available, it has tended to be based on relatively few observations (Wilkinson et al. 2003; Northridge et al. 2005; Hamer and Goldsworthy 2006; Jaiteh et al. 2013, 2014; Wakefield et al. 2014).

The very nature of mid-water trawl operations in the SPF, i.e. targeting key prey species for fur seals (Gales and Pemberton 1994; Page et al. 2005a, Littnan et al. 2007; Kirkwood et al. 2008) at depths well within their diving range (Arnould and Hindell 2001; Page et al. 2005b) means that operational interactions are inevitable. Our data demonstrate that such interactions are common, with interactions observed in over half of the monitored trawls. Interactions involving dolphins are also known to occur in this fishery but were not observed, implying that they are much more sporadic in occurrence.

Fur seal interaction rates increased with the level of recent trawl effort. This implies learning or habituation to the fishing activities, noting that the vessel was the only trawler

operating in the SPF at that time. Presumably seals were initially attracted to the trawl operation, removing fish from the net at or near the surface, as well as foraging on discards, but gradually learnt to forage from within the net itself. Such a finding is consistent with that for the deep water factory trawl fishery for blue grenadier (*Macruronus novaezelandiae*) that operates off western Tasmania. In that fishery the number of Australian fur seals observed around fishing vessels increased with both the number of trawls and number of vessels operating in an area (Hamer and Goldsworthy 2006). Habituation to these fishing operations was further reinforced by the observation that individual Australian fur seals repeatedly targeted the offshore fishery throughout the duration of the fishing season, resting between foraging trips on coastal haul-outs (Tilzey et al. 2006).

Seals entered the mid-water trawl during all phases of the fishing operation, with significantly higher interaction rates whilst the gear was being set and during pump-out, although the magnitude of the latter effect was uncertain. Thus, with the exception of setting the gear, there was no clear evidence to indicate increased vulnerability of seals entering the net during operational phases that involved alterations to net geometry, i.e. turning and hauling. In absolute terms, over half of all interactions occurred whilst the net was fishing, a phase that accounted for over 70% of the total operational time. These observations differ from those for the blue grenadier trawl fishery. In that fishery Australian fur seals were only observed to enter the trawl when it was being set (descending) or hauled (ascending) but not during the fishing phase (Hamer and Goldsworthy 2006). Operational differences in trawl depth represent the primary reason for this difference. Trawl effort in the SPF is generally at less than 150 m depth, whilst the blue grenadier fishery operates in depths greater than 350 m, which is outside of the known diving capability of Australian fur seals (Arnould and Hindell 2001). In the blue grenadier fishery the greatest depth that an Australian fur seal was observed to have entered the trawl net was 190 m (Hamer and Goldsworthy 2006).

Trawl effort in the SPF was concentrated at night when the target species tend to form dense schools and as a result the majority of seal-trawl interactions occurred during the hours of darkness. Time of day did not, however, have a significant effect on interaction rates. These observations are in marked contrast to those of Hamer and Goldsworthy (2006) who reported that fur seal bycatch in the blue grenadier fishery occurred exclusively during day shots, even though about half of the trawl effort in that fishery occurred at night. The reasons for these differences are unclear since our data clearly demonstrate that fur seals actively dived on the trawl gear during the night as well as during the day. While we cannot entirely discount that lighting associated with the camera system may have influenced behavioural responses within the net, it is unlikely to have been a factor influencing whether seals entered the net at night, especially given the 150 m separation between the net mouth and SED.

Despite the lack of a seasonal effect on interaction rates, the number of sightings (interaction events) peaked in the second quarter (late autumn and early winter) and were lowest during the second half of the year (late winter to early summer). It is unclear whether this finding reflects differences in behaviour (activity levels) once in the trawl or is an artefact of sampling. The lack of seasonality in interaction rates would nevertheless seem to be more informative in understanding the nature of seal-fishery interactions in the SPF. Our findings differ from those for a demersal trawl fishery operating off southern and eastern Australia in which seal bycatch rates (not necessarily interactions) peaked during winter and were lowest during summer (Knuckey et al. 2002).

The vast majority of seals (>90%) entered the trawl via the mouth or forward part of the net, the escape opening representing a minor point of ingress. Unlike net entry, almost half of the seals were expelled out of the SED escape opening whereas slightly more than a quarter escaped via the net entrance. An escape opening was therefore crucial in determining

the fate of individual seals and the application of video technology enabled us to determine its effectiveness in a non-destructive manner.

Breath-hold duration is a critical determinant of survival in air breathing animals and it is perhaps significant that the maximum interaction duration for individuals that escaped by actively swimming out the net entrance was just over 6 min. Under natural conditions, maximum dive durations of 6.8 and 8.9 min have been recorded for male and female Australian fur seals, respectively (Hindell and Pemberton 1997; Arnould and Hindell 2001). New Zealand fur seals have reported dive durations of up to 14.8 min, the longest recorded for otariids studied to date (Page et al. 2005b). As the recorded vertical travel rate when diving for Australian fur seals is around 0.5 m s^{-1} (Hoskins and Arnould 2013) and mean descent rate for New Zealand fur seals just under 1.5 m s^{-1} (Harcourt et al. 2002), it could take more than a minute for an individual to dive to a depth of around 100 m, with additional time required to locate and enter the net and then return to the surface. Based on the dive capabilities of fur seals, in particular Australian fur seals, the potential for survival is expected to be high for interactions lasting less than about 5-6 min. However, the probability of survival is expected to decline as interaction times approach about 10 min, particularly at fishing depths. This implies the possibility of additional, cryptic mortality amongst individuals that were expelled from the net whilst still responsive. This issue was also highlighted by Robertson and Chilvers (2011) in relation to New Zealand sea lions (*Photarctos hookeri*), based largely on post mortem examination of sea lions captured in trawls. While there is controversy surrounding the interpretation of the necropsy results (see Hamilton and Baker 2015; Robertson 2015), any post escape mortality is unlikely to be quantified readily and thus the impacts of fishing on affected populations will be underestimated (see also a review by Gilman et al. 2013).

Mortalities occurred during each of the trawl phases and although there was no significant effect of trawl phase, recent fishing activity, time of day or season, the size of escape hole (but not whether it was open or partially obstructed) did represent a significant factor. Overall, the odds of mortality for an individual seal increased fivefold when the small rather than large escape opening was used. In the context of the trawl operations monitored, we estimate that 49 fur seals were killed during the eleven month period study period, suggesting an overall mortality rate of 0.26 seals trawl⁻¹. This rate could, theoretically, have been halved had the large escape opening configuration been used for the entire study period. Even with the large escape opening the mortality rate was still substantially higher than levels reported for other Australian trawl fisheries, such as the blue grenadier fishery (average of 0.047 seals trawl⁻¹) (Shaughnessy et al. 2003; Tilzey et al. 2006) and the South East Trawl fishery (average 0.019 seals trawl⁻¹) (Knuckey et al. 2002; Tuck et al. 2013). Our findings are generally consistent with observations from other fisheries which suggest that marine mammal bycatch rates tend to be higher in mid-water compared with demersal trawl fisheries (Wickens and Sims 1994; Fertl and Leatherwood 1997; Hall et al. 2000).

An obvious problem with the bottom opening configuration was the fact that all of the seals that had drowned dropped out of the escape opening before the net was retrieved on board. This has clear ramifications for the reporting of bycatch - even with a high level of observer coverage most, if not all, of the interactions would have gone undetected. Jaiteh et al. (2014) also noted this issue in respect to the dolphin bycatch in a demersal trawl fishery employing a bottom opening escape hatch. Dropout or the passive ejection of mortalities through escape openings is not, however, limited to bottom opening configurations and has been reported for top opening escape hatches (Wakefield et al. 2014; Robertson 2015).

Allen et al. (2014) suggested that bottom-opening escape hatches are not well suited for marine mammals which tend to try and swim upwards in an attempt to get to the surface

and argued for top opening escape hatches to reduce marine mammal bycatch. A top opening SED configuration was trialled briefly at the end of our study but since the hard grid could not be safely stored on the vessel's net drum its use was discontinued. Three seal interactions in ten trawl shots were observed with this configuration and in each case the animals were ejected out of the escape hole. The use of either a top opening SED with a hood or a barrier net located near the entrance of the trawl is now mandated for mid-water trawl operations in the SPF (AFMA 2015). The effectiveness of a top opening SED, however, requires further investigation, both for its potential to reduce bycatch but also to address the issue of unaccounted mortality arising from dropout.

Ultimately, developing strategies to mitigate seal interactions in the SPF requires changes to fishing practices and further refinement of the exclusion device. Movement away from areas with seals prior to shooting the gear, ensuring that the net is deployed and hauled rapidly, removing fish meshed in the nets and avoiding the discard of offal on the fishing grounds are strategies that have been implemented with some success in the blue grenadier fishery (Tilzey et al. 2006). Limiting the concentration of fishing effort in space and time could also effectively reduce interaction rates. It is also important to focus on how to maximise the survival of seals once in the trawl, and as such an exclusion device probably offers the most practical solution. The design of the exclusion device should not rely on 'problem solving' or sensory capabilities of the seals to navigate to the escape opening. Rather, animals should be directed to exit the net, whether actively searching/swimming or not, and the orientation of the grid and location and size of the escape opening will assist in this. At the same time, the ability to retain any animals that die in the trawl represents a critical design feature that needs to be evaluated. There is, therefore, considerable scope to further refine the SED design to reduce bycatch, whilst addressing concerns associated with

cryptic morality. The application of underwater video technology represents a promising tool in this endeavour.

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1 Table 1. Trawl effort, video coverage, number of interactions, mode of access and outcomes
 2 by SED configuration for mid-water trawl operations conducted off Tasmania between
 3 March 2006 and January 2007. Values in parenthesis represent percentages.

	SED configuration		
	Small escape	Large escape	Total
	opening	opening	
Total trawl shots (no.)	75	115	190
Trawl shots with video footage	30	48	78
Trawl shots with megafauna interactions	25	30	55
Trawl shots with fur seal interactions	25	27	52
Trawl shots with fur seals wholly inside the net	23	26	49
Estimated number of fur seals wholly inside the net	56	90	146
Net access			
Net entrance	51 (91.1)	85 (94.4)	136 (93.2)
SED escape opening	4 (7.1)	5 (5.6)	9 (6.2)
Uncertain	1 (1.8)	0	1 (0.7)
Interaction outcome			
Escaped (net mouth or meshes)	16 (28.6)	22 (24.4)	38 (26.0)
Expelled (SED escape opening)	18 (32.1)	51 (56.7)	69 (47.3)
Uncertain	8 (14.3)	11 (12.2)	19 (13.0)
Mortality	14 (25.0)	6 (6.7)	20 (13.7)

5 Table 2. Significance (p-values) of factors tested in the interaction and mortality models;
6 non-significant values (not bolded) are those obtained prior to removal of that variable from
7 the model. n/t not tested

Factor	Interaction models		
	Identified	Interaction	Mortality
	seal	event	model
Recent fishing	0.00	0.00	0.20
Trawl phase	0.01	0.11	0.23
Time of day	0.44	0.19	0.91
Season	0.23	0.02	0.96
SED			
configuration	n/t	n/t	0.002
Escape opening	n/t	n/t	0.41

8

9 Table 3. Model coefficients and odds ratios for significant factors in the identified seal,
 10 interaction event and mortality models.

Factor	Estimate	SE	Z	p	Odds ratio	
					95%	
					confidence interval	
Seal model						
Intercept	-2.99	0.22	-13.44	0.00		
Recent Fishing	0.02	0.00	5.15	0.00	1.03	1.02-1.04
Setting	1.08	0.32	3.33	0.00	2.93	1.57-5.50
Turning	0.31	0.32	0.96	0.34	1.37	0.71-2.56
Hauling	-0.06	0.43	-0.14	0.89	0.94	0.38-2.13
Pump-out	0.78	0.43	1.81	0.07	2.18	0.93-4.99
Interaction event model						
Intercept	-2.23	0.44	-5.08	0.00		
Recent Fishing	0.04	0.01	5.43	0.00	1.04	1.02-1.05
Q2 (Apr-Jun)	0.31	0.42	0.73	0.46	1.36	0.56-3.11
Q3 (Jul-Sep)	-0.64	0.42	-1.51	0.13	0.53	0.22-1.14
Q4 (Oct-Dec)	-0.48	0.54	-0.89	0.38	0.62	0.21-1.76
Mortality model						
Intercept	-1.00	0.31	-3.19	0.00		
SED large opening	-1.58	0.53	-3.00	0.00	0.21	0.07-0.56

1 FIGURE CAPTIONS

2 Figure 1. Map of Tasmania showing the location of mid-water trawl shots undertaken
3 during the study period, regions referred to in the text are indicated. Black circles
4 indicate trawls involving seal interactions, grey circles indicate monitored trawls
5 without interactions and open circles indicate unmonitored shots.

6

7 Figure 2. Underwater views of the bottom opening SED showing the small escape
8 opening (left) and large escape opening (right) configurations.

9

10 Figure 3. Box and whisker plot of interaction durations based on outcome or, for
11 mortalities, the duration of overt responsiveness. An outlier is represented by the black
12 dot.

13

Figure 1. Map of Tasmania showing the location of mid-water trawl shots undertaken during the study period, regions referred to in the text are indicated. Black circles indicate trawls involving seal interactions, grey circles indicate monitored trawls without interactions and open circles indicate unmonitored shots.

Figure 2. Underwater views of the bottom opening SED showing the small escape opening (left) and large escape opening (right) configurations.

Figure 3. Box and whisker plot of interaction duration based on outcome or, for mortalities, the duration of overt responsiveness. An outlier is represented by the black dot.